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The relative contribution of various external sources for five major ecosystems is delineated. Discussion of seasonal and long-term trends of external sources is presented. The impact of external sources on the eutrophication process is evaluated. A scale of eutrophication for estuarine ecosystems is suggested for comparing the impact of nutrient enrichment.

Comparisons of external nutrient loadings and the scale of eutrophication for 13 estuarine and freshwater ecosystems are made. A detailed comparison of the five estuaries of the Chesapeake Bay is presented from which relationships between external nutrient loadings ($g/m^2/yr$) and eutrophic conditions are suggested.

Analysis of the relationship between external nutrient loadings, nitrogen/phosphorus ratio, and eutrophic state suggests that, for the East Coast estuarine ecosystems, if the phosphorus loading is 1.0 $g/m^2/yr$ or less, excessive eutrophic conditions can be prevented. The favorable response of the Potomac estuary to phosphorus control demonstrates that excessive eutrophic conditions may be alleviated with advanced wastewater treatment, depending on many factors including nutrient loadings.

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SOURCES OF NUTRIENTS AND THE SCALE OF EUTROPHICATION PROBLEMS IN ESTUARIES

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ABSTRACT: A comprehensive analysis of external sources of nutrients is presented including an impact, comparison of external loadings, and the resulting scale of eutrophication. The major emphasis of the analysis is on nitrogen and phosphorus.

The relative contribution of various external sources for five major ecosystems is delineated. Discussion of seasonal and long-term trends of external sources is presented. The impact of external sources on the eutrophication process is evaluated. A scale of eutrophication for estuarine ecosystems is suggested for comparing the impact of nutrient enrichment.

Comparisons of external nutrient loadings and the scale of eutrophication for 13 estuarine and freshwater ecosystems are made. A detailed comparison of the five estuaries of the Chesapeake Bay is presented from which relationships between external nutrient loadings ($g/m^2/yr$) and eutrophic conditions are suggested.

Analysis of the relationship between external nutrient loadings, nitrogen/phosphorus ratio, and eutrophic state suggests that, for the East Coast estuarine ecosystems, if the phosphorus loading is 1.0 $g/m^2/yr$ or less, excessive eutrophic conditions can be prevented. The favorable response of the Potomac estuary to phosphorus control demonstrates that excessive eutrophic conditions may be alleviated with advanced wastewater treatment, depending on many factors including nutrient loadings.

INTRODUCTION

Nutrient budgets are necessary in understanding and in aiding control of the eutrophication process. Most nutrient budgets have been developed for total phosphorus and total nitrogen. Recently, analytical methods have been improved and their cost reduced, thus facilitating the addition

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of other forms of nitrogen and phosphorus in routine field studies. Many of the budgets focus on external sources, but the internal sources and sinks within a given water body have also been considered.

This paper focuses on external sources of nutrients (particularly nitrogen and phosphorus), their impact and the comparison of external loadings, and the resulting scale of eutrophication. Nutrient sources of five major ecosystems are discussed. Seasonal and long-term trends are examined for Chesapeake Bay. The impact of eutrophication is evaluated and a scale of eutrophication for estuarine ecosystems is proposed. Comparisons of external nutrient loadings and the scale of eutrophication for 13 select estuarine systems and freshwater lakes are made. A more detailed analysis is presented for the Chesapeake Bay and its five major estuaries.

EXTERNAL NUTRIENT BUDGETS FOR FIVE MAJOR ECOSYSTEMS

External Budget for the Hudson River Basin

For the Hudson River basin, the external loadings of phosphorus and nitrogen have been combined into two sources, municipal/industrial and land runoff as shown in Table 1 (29, 44). The major external loading of

TABLE 1. Annual External Nutrient Budget - Hudson River Basin - (1968).

Source	Phosphorus (kg/day)	Nitrogen (kg/day)
Municipal/Industrial	8,000	36,000
Land Runoff	3,000	21,000
Total	11,000	57,000

phosphorus was from municipal and industrial sources, which contributed about 73 percent of the total. Likewise, for nitrogen the major source in the external budget was municipal and industrial sources with a contribution of 63 percent of the total.

External Nutrient Budget for San Joaquin Delta

The external nutrient budget for the San Joaquin delta which flows into San Francisco Bay is shown in Table 2 (3). The major source of phosphorus was municipal wastewater discharges, about 60 percent of the total input. For nitrogen, the major source was industrial discharges, about 47 percent of the total. While land runoff currently is not a major

TABLE 2. Annual External Nutrient Budget - San Joaquin Delta - (1968).

Source	Phosphorus (kg/day)	Nitrogen (kg/day)
Municipal	4,000	11,000
Industrial	200	15,000
Land Runoff	2,500	6,000
Total	6,700	32,000

part of the total external nutrient budget, it is anticipated that by the year 2000, nitrogen loading from this source will be the largest nitrogen contribution to the delta, primarily from irrigation return systems. A plan to manage agricultural drainage is currently being developed (47).

External Nutrient Budget for Lake Superior

Although Lake Superior is not an estuarine system, the nutrient budget shown in Table 3 introduces an interesting aspect of atmospheric nutrient

TABLE 3. Annual External Nutrient Budget - Lake Superior - (1975).

Source	Phosphorus (kg/day)	Nitrogen (kg/day)
Municipal/Industrial	500	3,000
Land Runoff	6,300	100,000
Air	3,000	153,000
Shoreline Erosion	700	4,000
Total	10,500	260,000

input (19). The major source of phosphorus was land runoff, with a contribution of approximately 60 percent. The second largest phosphorus source was the air. For nitrogen, however, the major contribution (59 percent) was from the air. Land runoff was the second largest contributor, providing 38 percent of the total nitrogen.

External Nutrient Budget for the Potomac Estuary

Table 4 shows the contribution of nutrients to the Potomac estuary from the upper Potomac basin and from the wastewater discharges of the Washington, D.C. metropolitan area (27, 28). As can be seen in Table 4, the major contribution of total phosphorus (84 percent) was from

TABLE 4. Annual External Nutrient Budget - Potomac Estuary (1969-1970).

Parameter	Upper Potomac River Basin (kg/day)	Wastewater Discharges (kg/day)	Total (kg/day)
Total Phosphorus	2,080	11,300	13,380
Inorganic Phosphorus	1,200	8,600	9,800
Organic Phosphorus	880	2,700	3,580
Total Nitrogen	26,880	27,300	54,180
NH_3 Nitrogen	2,080	24,100	26,180
NO_2 and NO_3 Nitrogen	16,700	500	17,200
Organic Nitrogen	8,100	2,700	10,800
Total Organic Carbon	182,000	36,400	218,400
Total Carbon	795,000	102,300	897,300

wastewater discharges. The major component of total phosphorus was in the inorganic form. The total nitrogen input to the estuary was 54,180 kg/day in 1969-1970, of which approximately 50 percent was from wastewater discharges in the Washington area and the remainder from the upper Potomac basin, which includes both point and nonpoint sources. The major form of nitrogen from wastewater discharges was ammonia, while the predominant form from the upper Potomac basin was nitrate. Table 4 also shows the total organic carbon and total carbon loadings to the estuary. The major contribution of carbon, both inorganic and organic, was from the upper basin.

External Nutrient Budget for Chesapeake Bay

The external nutrient budget for Chesapeake Bay, as shown in Table 5, is presented in two systems, the entire Bay and the Bay proper (9, 12, 17, 27, 28, 41, 46). The first system includes the nutrient budget for the entire Bay, which includes the Patuxent, Potomac, Rappahannock, York, and James estuarine systems. The budget also is presented for only those discharges into the Bay proper, thus not including the five above-mentioned estuaries.

The major source of phosphorus entering the entire Chesapeake Bay was wastewater discharges within the tidal ecosystem, about 69 percent of the total. The major nitrogen contribution, approximately 68 percent, was from the upper basin land runoff. The term "upper basin land runoff" includes both point and nonpoint contributions. For the Bay proper, the major source of phosphorus (72 percent) was wastewater discharges. The largest nitrogen loading to the Bay proper was from runoff (71 percent).

TABLE 5. Annual Nutrient Budget - Chesapeake Bay - (1971).

Source	Phosphorus (kg/day)	Nitrogen (kg/day)
Entire Chesapeake Bay Including Estuaries		
Municipal/Industrial	28,700	87,700
Upper Basin Land Runoff	10,200	195,400
Air	2,500	14,800
Total	41,400	297,900
Chesapeake Bay Proper Excluding Estuaries		
Municipal/Industrial	16,900	45,900
Upper Basin Land Runoff	5,200	131,500
Air	1,400	8,200
Total	23,500	185,600

Discussion

For the five systems, the largest phosphorus and nitrogen sources are:

	Ecosystem Watershed Description	Largest Phosphorus Source	Largest Nitrogen Source
Hudson	Forested/ Industrial/ Urban	Wastewater Discharges (73%)	Wastewater Discharges (63%)
San Joaquin	Agricultural/ Industrial/ Urban	Wastewater Discharges (60%)	Wastewater Discharges (47%)
Lake Superior	Forested/ Rural	Land Runoff (60%)	Air (59%)
Potomac Estuary	Forested/ Urban	Wastewater Discharges (84%)	Wastewater/Land Runoff (50%) (50%)
Chesapeake Bay	Forested/ Industrial/ Urban	Wastewater Discharges (69%)	Land Runoff (68%)

As can be seen in the above tabulation, the major source of phosphorus or nitrogen can vary from ecosystem to ecosystem. Likewise, the relative percent contribution of a given source can also vary significantly depending on the geographical location, industrial/urban development,

and agricultural practices.

SEASONAL AND LONG-TERM TRENDS OF EXTERNAL NUTRIENT INPUTS

Seasonal Nutrient Input Variations

For the upper Potomac basin, which is above the fall line near the nation's capital, nutrient inputs are presented in Tables 6 (1966) and 7 (1969-70) (26, 35, 48).

TABLE 6. Seasonal Nutrient Inputs - Upper Potomac River Basin (1966).

	Flow (m^3/s)	Phosphorus (kg/day)	Nitrogen (kg/day)
January	450	4,000	44,700
February	550	5,100	60,300
March	700	6,600	85,900
April	670	6,300	79,300
May	480	4,300	48,900
June	290	2,300	23,300
July	180	1,300	11,900
August	200	1,500	14,000
September	160	1,200	9,800
October	210	1,600	14,700
November	220	1,700	15,500
December	330	2,700	28,100
Average	370	3,200	36,400

To illustrate variations in seasonal contributions, the hydrologic flow pattern for 1966 (Table 6) was typical for the Potomac system with 1969-1970 (Table 7) being a period of low spring flows. As can be seen in Tables 6 and 7, the monthly contributions of phosphorus and nitrogen usually follow the monthly flow hydrograph with significant variations in monthly contribution of nutrients, such as for the month of February. For the upper Potomac River basin, streamflows are usually high in the spring months and low in the summer months. However, in comparing August,1966 and August, 1969, a considerably larger contribution of nutrients was observed in 1969.

A flow versus nutrient-input relationship has been developed as can be seen in Table 8 for the Susquehanna River basin above Conowingo Dam (8). When the flow is at 335 m^3/s, the phosphorus contribution is

TABLE 7. Seasonal Nutrient Inputs - Upper Potomac Basin (February 1969 - February 1970).

Month	Flow (m^3/s)	T. Phosphorus (kg/day)	Inorganic Phosphorus (kg/day)	TKN-Nitrogen (kg/day)	NH_3-Nitrogen (kg/day)	NO_2+ NO_3 (kg/day)	Total Nitrogen (kg/day)
Feb	220	2,040	950	10,100	2,150	10,500	20,600
Mar	280	2,500	1,500	12,000	2,400	20,600	32,600
Apr	230	2,150	1,000	10,300	2,300	9,900	20,200
May	130	1,250	400	5,300	1,700	3,600	8,900
Jun	70	700	200	3,500	950	1,300	4,800
Jul	80	800	250	3,850	1,000	2,250	6,100
Aug	270	2,400	1,250	12,000	2,400	14,500	26,500
Sep	145	1,300	500	6,700	1,550	4,600	11,300
Oct	75	800	200	3,750	1,050	1,450	5,200
Nov	120	1,150	400	5,400	1,400	3,200	8,600
Dec	265	2,900	1,350	11,800	2,350	17,900	29,700
Jan	395	3,550	2,550	17,700	3,150	3,950	21,650
Feb	715	7,000	5,250	30,300	4,850	87,250	117,550
Average	230	2,100	1,200	10,200	2,100	14,000	24,000

TABLE 8. Flow/Nutrient - Input Relationships - Susquehanna River - (1969-1970).

Flow (m^3/s)	Total Phosphorus (kg/day)	Inorganic Phosphorus (kg/day)	Inorg-P Total-P (%)	Total Nitrogen (kg/day)	Inorganic Nitrogen (kg/day)	Inorg-N Total-N (%)
335	1,100	500	45	36,400	26,400	73
1,670	7,000	4,150	59	181,000	134,600	74
3,350	16,500	10,500	64	363,600	272,800	75

estimated to be 1100 kg/day, with nitrogen 36,400 kg/day. However, when the flow is at 3,350 m^3/s, the estimated phosphorus contribution increases about 15-fold to 16,500 kg/day, and the nitrogen increases about 10 fold to 363,600 kg/day. The percentage of inorganic phosphorus increases substantially as the flow increases, while the percentage of inorganic nitrogen increases only slightly as the flow increases.

Long-term Nutrient-Input Variations

To demonstrate the annual variability in land runoff contributions of nutrients, data obtained from analysis of the raw water intake of the District of Columbia water treatment plant were utilized (27). The data in Table 9 show the annual variation of flow and of nitrate nitrogen input.

TABLE 9. Annual Variation in Nitrate Input - Potomac River Basin.

Year	Mean Flow (m^3/s)	Annual Nitrate Nitrogen Input (kg/day)
1960	360	20,000
1961	400	19,900
1962	355	16,400
1963	265	12,100
1964	310	15,900
1965	270	12,100
1966	225	17,400
1967	360	35,000

As can be seen in Table 9, there can be a significant yearly input of nitrate nitrogen which is the major form of nitrogen input into the estuary. The annual nitrate input increased over 2.0-fold during the 1966-1967 period, with a corresponding stream flow increase of 1.6-fold.

Long-term trends of nutrient contributions from wastewater discharges in the Washington, D.C. metropolitan area to the Potomac estuary are shown in Table 10 (27). In 1913, phosphorus and nitrogen loadings were

TABLE 10. Wastewater Loading Input Trends - Potomac Estuary (Washington, D.C., Metropolitan Area).

Year	Population	Wastewater Flow (m^3/sec)	Phosphorus (kg/day)	Nitrogen (kg/day)
1913	320,000	1.8	500	2,900
1932	575,000	3.2	900	5,200
1954	1,590,000	8.3	2,500	14,400
1960	1,860,000	9.5	4,550	16,900
1965	2,100,000	12.2	8,500	19,100
1970	2,600,000	13.9	11,000	27,300
1977	2,880,000	15.4	3,409	23,000
1978	3,140,000	16.8	2,600	24,900
1979	3,290,000	17.6	2,400	22,700

about 500 and 2,900 kg/day, respectively. These nutrients increased to a maximum of about 11,000 kg/day of phosphorus and 27,300 kg/day of nitrogen in 1970. However, with the initiation of advanced waste treatment at the wastewater facilities, the total phosphorus contribution to the estuary in 1979 had been reduced significantly to 2,400 kg/day, with a lesser reduction in nitrogen loadings to about 22,700 kg/day.

Discussion

The data for the Potomac estuary of the Chesapeake Bay ecosystem, as presented in Tables 6 and 7, demonstrate vividly that the seasonal contribution from land runoff can vary from month to month in a given year, and from year to year as shown in Table 8. For example, for the months of July and August, 1969, there was three-fold increase in phosphorus loading from the upper basin. Moreover, when the nitrogen contribution in February, 1969 is compared to February, 1970, a 5.7-fold increase can be seen.

For estuaries with rather short hydraulic retention times and large contributions from land runoff, it may be necessary to express external nutrient loading on either a seasonal or monthly basis.

In developing and evaluating control strategies, it is necessary to determine these loadings on a long-term statistical basis. As part of a nutrient input study of the Chesapeake Bay in 1969-1971 (8), a detailed analysis of stream flow and nutrient contributions from the major rivers was made. For seven major river systems, a high correlation between monthly flow and monthly phosphorus and nitrogen loading was obtained.

Utilizing such relationships and historical streamflow records, it is

possible, with proper use of statistical techniques, to determine estimates of contributions from land runoff. These techniques can add significantly in determining the contribution from land runoff on a more reliable statistical basis and in analyzing historical responses of an ecosystem. In addition, an analysis of population trends and wastewater flows, as demonstrated for the Potomac estuary, can be used in determining historical contributions from municipal discharges.

IMPACT AND SCALE OF THE EUTROPHICATION PROCESSES

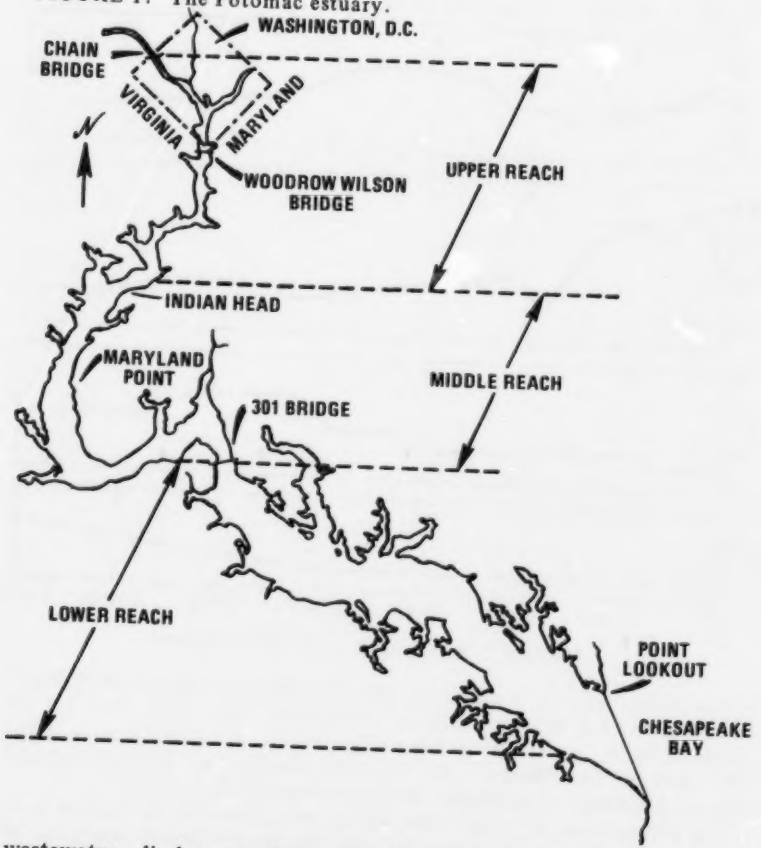
To illustrate the impact of external nutrient loadings on the eutrophication process, data from the Potomac estuary (see Figure 1) collected in a survey on July 8, 1977, are shown in Figures 2, 3, and 4 (6). Figure 1 shows the Potomac estuary divided into three major reaches. The upper reach, 64 kilometers (40 miles), is tidal and mainly fresh water. Freshwater blue-green algal blooms are dominant in the summer. Over 15 m^3/s of wastewater is discharged into the upper reach from 12 major treatment facilities serving the Washington, D.C. metropolitan area. The middle reach, where salt water intrusion occurs, is often referred to as the transition zone. The lower reach begins 107 kilometers (67 miles) below Chain Bridge where salt water intrusion from Chesapeake Bay is large, often reaching 16,000 mg/l. The bottom waters of the lower reach frequently become anoxic during the summer.

The physiological data of the upper and middle reaches of the Potomac estuary are shown in Figure 2, including pH, temperature, transparency, and salinity. The pH remained relatively constant, while temperature decreased slightly in the middle reach of the estuary. In the upper reach, the transparency was generally low, as a result of high sediment loadings from the upper river basin and from high turbidity loadings from the wastewater discharges, but increased below Milepoint 40. The salinity intrusion began about Milepoint 40.

Figure 3 shows the major forms of phosphorus. The large increase in phosphorus at Milepoint 8 was due to contributions from wastewater discharges. The total phosphorus remained relatively constant after Milepoint 8 in the upper reach, with a slight decrease around Milepoint 40. Although the major form of phosphorus from the wastewater plants was inorganic, the major form at Milepoint 10 was organic. It appears that the inorganic form was utilized bacterially and converted into the organic form during assimilation of the carbon and nitrogen from the wastewater discharges. Farther down the estuary, the major form was still organic and can be attributed mainly to phosphorus in the algal cells. Below Milepoint 40, when saltwater intrusion began, there was remineralization, and inorganic phosphorus became the predominant form at Milepoint 44.

Figure 4 shows the concentration of various forms of nitrogen along the estuary. At Milepoint 8, the large increase in nitrogen was due to

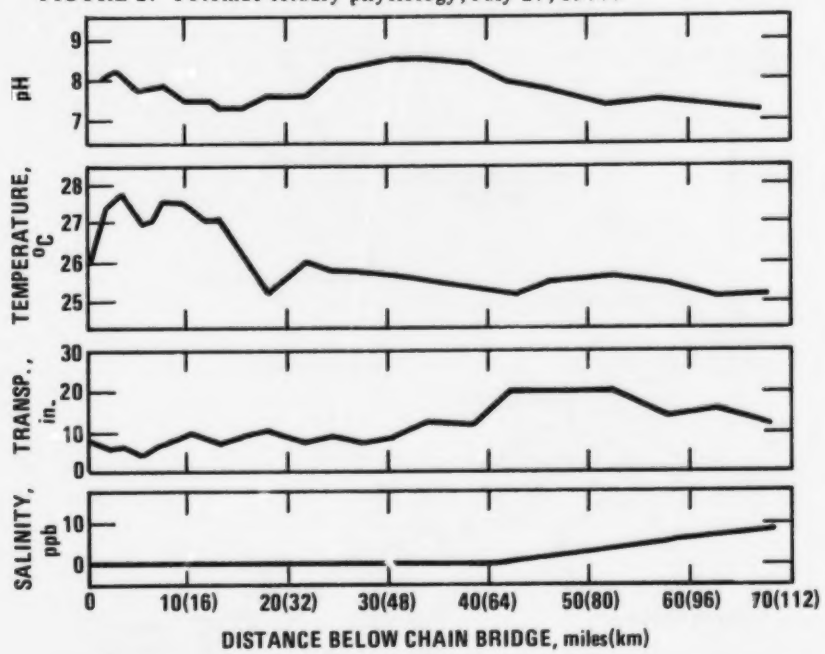
FIGURE 1. The Potomac estuary.



wastewater discharges. However, the total concentration decreased sharply, in contrast to phosphorus, in the lower part of the upper reach. Although the major form of nitrogen from the wastewater plants was as ammonia, it was quickly oxidized to the nitrate form, as indicated in Figure 4. A large portion of the nitrate nitrogen was incorporated into algal nitrogen. Below Milepoint 40, remineralization began to take place and ammonia increased. The predominant form below Milepoint 40 was organic nitrogen.

Figure 5 presents the carbon and chlorophyll concentrations along the estuary for the same time period. The chlorophyll level reached a maximum of about 120 μg/l below Milepoint 30. Total carbon concentrations remained essentially constant throughout the length of the

FIGURE 2. Potomac estuary physiology, July 27, 1977.

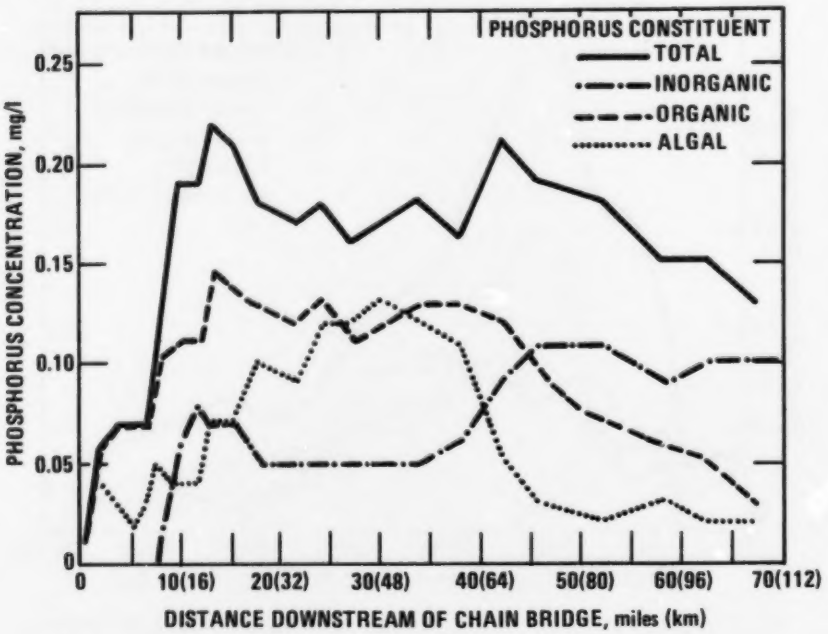


upper estuary. However, as can be seen in Figure 5, organic carbon began to increase significantly around Milepoint 30, with the largest contribution to the increase attributed to the die-off of algal blooms. High total carbon contribution and resulting biochemical oxygen demand reduced the dissolved oxygen in the lower reach (5, 27).

The phosphorus, nitrogen, and carbon data presented in Figures 3, 4, and 5 represent typical nutrient dynamics of the Potomac estuary during summer conditions. Of the approximately 25,000 kg/day (see Table 4) of ammonia nitrogen discharged into the upper reach, almost all is oxidized to nitrate nitrogen. More dissolved oxygen resources are needed to oxidize the ammonia than are required by the carbonaceous material discharged from the wastewater facilities into the upper reach (5, 27).

The nitrate nitrogen is rapidly utilized by the planktonic community in the upper Potomac estuary. The concomitant conversion of inorganic carbon to organic carbon is over 100,000 kg/day or about 300 percent more than from the total organic carbon loading from wastewater discharges (27). Similar calculations for the Hudson estuary and New York Bight by Garside, et al. (15) indicate that the eutrophication process contributes about 43 percent of the total organic carbon to these

FIGURE 3. Major forms of phosphorus in Potomac estuary.



estuarine systems.

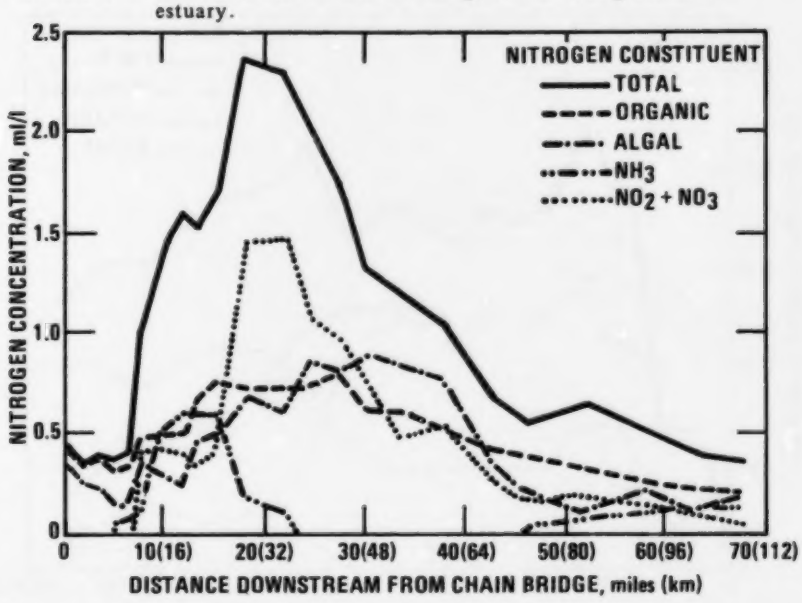
Studies of the Pamlico River estuary (10), Albermarle Sound (4, 52), and Oslo Fjord (2) have also attributed the high organic content in these estuarine systems mainly to planktonic growths. Anoxic conditions in the lower depths of Oslo Fjord are also attributed mainly to the eutrophication process.

Field and mathematical simulation studies of the Potomac estuary by Clark and Jaworski (5) have indicated that algal photosynthesis and respiration are a major component in the dissolved oxygen budget. Sensitivity analyses have shown that algal photosynthesis and respiration rates are of paramount importance in developing the dissolved oxygen budget of the Potomac estuary. At times, the dissolved oxygen condition can be depressed from 1.0 to 4.0 mg/l, attributed to algal respiration.

Discussion

High external nutrient loadings and the resulting eutrophication process can have three directly measurable impacts on the dissolved oxygen of an estuarine system: 1) a biochemical oxygen demand exerted by the oxidation of ammonia nitrogen, 2) a biochemical oxygen demand in the

FIGURE 4. Concentration of various nitrogen forms along Potomac estuary.

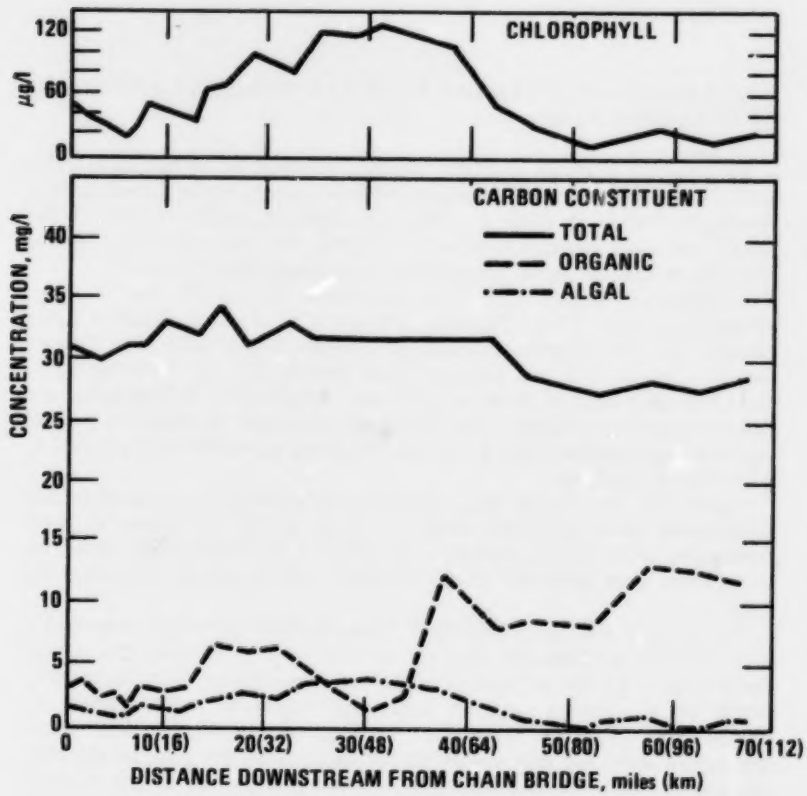


water column created by the conversion of inorganic carbon to organic carbon, and 3) a significant increase in total organic carbon of the system and its secondary impact, such as the benthic oxygen demand. There also can be an impact on the dissolved oxygen demand due to photosynthesis and respiration.

For freshwater lakes, general descriptive terms of the scale of eutrophication (i.e., oligotrophic, mesotrophic, and eutrophic) have been successfully used by Vollenweider (51) and others. Depending on the authors, the descriptive terms included both an indication of the degree of nutrient enrichment and the impact of the enrichment on the ecosystem.

Attempts have been made to develop both scientific and management indexes by McErlean and Reed (36) and water quality criteria by Jaworski and Villa (30) to aid in providing a scale of eutrophication for estuary ecosystems. However, due to the lack of definitive and comparable data for a large number of estuarine ecosystems, a simpler approach was utilized for a general scale similar to the descriptive term used for freshwater lakes. The subjective description scale as proposed below focuses mainly on the impact of nutrient enrichment on the ecosystem rather than on the degree of nutrient enrichment; i.e., the concentration of phosphorus or nitrogen. This approach was taken in that portions of many estuaries which are highly enriched can be light limited, thus having

FIGURE 5. Carbon and chlorophyll concentrations along Potomac estuary.



no major eutrophication problems.

For relative comparative purposes, the subjective descriptions of the scale of eutrophication for estuarine ecosystems proposed are as follows:

Hyper-eutrophic - Indicative of very excessive nuisance conditions, anoxic conditions, and "undesirable" biological communities.

Eutrophic - Indicative of excessive nuisance conditions, low dissolved oxygen concentrations, and "undesirable" biological communities.

Non-Eutrophic - Indicative of biologically healthy and productive ecosystems with "desirable" biological communities.

The above estuarine environments are incorporated into a comparison of external loadings versus the scale of eutrophication as presented in the following section.

COMPARISON OF EXTERNAL NUTRIENT LOADINGS AND SCALE OF EUTROPHICATION

To compare external nutrient loadings of select water bodies and the scale of eutrophication, a tabulation of data from 13 ecosystems has been developed, shown in Table 11. The 13 ecosystems include 3 lakes in the North American continent: Superior (19, 43, 49), Baptiste (45), and Erie (43, 49); 6 U.S. estuarine ecosystems: Chesapeake Bay (9, 13, 17, 27, 41, 46), Potomac estuary (17, 27), Albemarle Sound (4, 16, 18, 39), Narragansett Bay (37), Delaware estuary (7, 38), and Pamlico River estuary (32, 33); 3 European estuarine systems: Archipelago (31), Thames estuary (11, 20, 21), and River-on-Tyne estuary (22, 23); and the North Sea (24). Data used in these comparisons, including the hydrographic and external nutrient budgets, were obtained from various literature sources and from unpublished files. In certain instances, data were extrapolated to aid in the comparison.

Except for the North Sea, the estuarine ecosystems utilized in this comparison have relatively shallow average depths compared to most freshwater lakes, usually ranging from about 4 to 9 meters. The estuarine ecosystems have relatively short retention times, usually less than one year.

For comparative purposes, the nutrient budgets have been normalized into nutrient loadings (in $g/m^2/yr$ or $g/m^3/yr$) by dividing the annual budget (g/yr) by the ecosystem surface area (m^2) or by the volume (m^3), based on a concept used in analyzing freshwater lake systems by Vollenweider (50). The normalized loadings are presented in both grams per square meter per year and grams per cubic meter per year. In addition, the atomic ratio of total nitrogen to total phosphorus of the external loadings and a subjective description including the scale of the eutrophic condition of the ecosystem are presented. The scale of eutrophication for a given ecosystem was obtained directly, or interpreted from, the data sources referenced and/or in some cases from personal knowledge of the author.

As can be seen from Table 11, the external phosphorus loadings on the surface area basis varied from 0.04 $g/m^2/yr$ for Lake Superior to over 190 $g/m^2/yr$ for the Tyne estuary. For nitrogen, the external loading on a surface area basis varied from 1.0 $g/m^2/yr$ for the North Sea to 750 $g/m^2/yr$ for the Tyne estuary. Using the North Sea and Lake Superior for comparison purposes, estuarine ecosystems had a significantly higher phosphorus and nitrogen loading. The highest loadings were for the Delaware, Thames, and Tyne estuaries. All three have short retention

times, receive a high contribution of industrial waste, and have no major algal bloom problems.

For the Narragansett, Albemarle, and Chesapeake estuarine ecosystems, nutrient loadings were very comparable. These three ecosystems can be considered to be healthy with no "excessive" eutrophication problems. However, some of the estuaries of Chesapeake Bay do have excessive eutrophic conditions. The Potomac estuary, an estuary of the Chesapeake, had considerably higher external loading and was considered to be hyper-eutrophic. However, there has been a significant decrease in phosphorus loading due to the recent institution of advanced waste treatment.

Phosphorus loadings to the estuarine ecosystems presented in Table 11 were all higher than for Lake Erie. In general, it appears that the higher the phosphorus loading, the more excessive were the eutrophic conditions. Nitrogen loadings into the estuarine systems were also generally higher than Lake Erie except Albermarle Sound and Narragansett Bay. Albemarle Sound appeared to be phosphorus limited (4), while Narragansett Bay appeared to be nitrogen limited (37).

Using the concept of the nitrogen to phosphorus ratio as developed by Redfield (40), insight can be gained into the possible limiting nutrient based on the nitrogen to phosphorus (N/P) ratio of external nutrient loadings. The ratios presented in Table 11 are for total nitrogen and total phosphorus. The nitrogen to phosphorus ratios presented in Table 11 suggest that most of the estuarine systems were nitrogen limited (an N/P below 16 is assumed to be nitrogen limited). When compared to Lake Superior and Lake Erie, which had N/P ratios of 60 and 27, respectively, and which were considered to be phosphorus limited, Albemarle Sound and Chesapeake Bay also appeared to be phosphorus limited.

For the ecosystem presented in Table 11, a rigorous comparison of external nutrient loadings and the scale of eutrophication is difficult to make unless physical factors such as depth and retention time as utilized by Vollenweider (50), Jaworski (25), and Lee (34) are included. To facilitate a more rigorous comparison, a detailed analysis was made of six estuarine ecosystems as presented in Table 12 with similar hydrodynamic configurations and a fairly consistent historical data base. The five estuaries of the Chesapeake Bay are generally long and narrow with the major wastewater discharges at the headwaters of the estuarine ecosystem. Average depth and retention times are comparable and the upper reaches, although tidal, are mainly freshwater systems. The watersheds of the estuaries have generally similar land use patterns, streamflow characteristics, and climatological conditions. The large differences in nutrient loadings among the estuaries and the institution of phosphorus removal at major wastewater treatment facilities discharging into the Upper Potomac estuary greatly enhance these detailed comparisons.

For the 1969-1971 time frame, a comparison of the external loadings for nitrogen and phosphorus indicates that the Potomac, James, and

TABLE 11. External Nutrient Loadings for Selected Ecosystems.

Ecosystem	Description	Surface Area (m^2)	Volume (m^3)	Average Depth (m)	Average Retention Time (yr)
North Sea (1972)	Non-eutrophic	575,000	54,000,000	93.3	--
Lake Superior (1976)	Oligotrophic lake	81,450	1,900,000	233.7	177.0
Lake Erie (1976)	Eutrophic lake	25,750	470,000	18.2	2.5
Chesapeake Bay with tribs. (1969-1971)	Localized eutrophic conditions	11,500	74,000	6.5	1.16
Potomac Estuary (1969-1971)	Hyper-eutrophic estuary	1,250	7,150	5.8	1.07
Albemarle Sound (1974)	Non-eutrophic	1,250	6,500	4.3	0.42
Narragansett Bay (1977)	Non-eutrophic	450	2,200	8.8	0.14
Delaware Estuary (1976)	Highly Industrial	300	1,330	4.3	0.22
Pamlico River Estuary (1976)	Eutrophic	230	980	4.2	0.71
Archipelago-Stockholm (1971) with nitrogen fixation	Eutrophic estuary	210	--	--	--
Thames Estuary (1971)	Highly Industrial	112	850	6.7	0.10
Baptiste Lake (Canada) (1977)	Naturally eutrophic lake	9	85	9.3	4.75
Tyne Estuary (1972)	Dissolved Oxygen problems	6	55	9.2	0.04

TABLE 11. (cont'd)

	External Phosphorus Loading			External Nitrogen Loading			Atomic N/P Ratio of Loading
	(g/yr) (10^6)	$(g/m^2/yr)$	$(g/m^3/yr)$	(g/yr) (10^6)	$(g/m^2/yr)$	$(g/m^3/yr)$	
North Sea	93,440	0.16	0.0017	565,000	1.0	0.01	14
Lake Superior	3,600	0.04	0.0003	95,200	1.2	0.01	60
Lake Erie	20,000	0.77	0.042	238,700	9.3	0.5	27
Chesapeake Bay	51,100	1.31	0.20	109,100	9.5	1.5	16
Potomac Estuary	5,300	4.30	0.74	25,200	20.2	3.5	11
Albemarle Sound	1,050	0.80	0.16	8,900	7.1	1.4	20
Naragansett Bay	820	1.82	0.29	2,200	4.9	0.8	6
Delaware Estuary	5,670	18.90	4.21	30,000	100.0	22.5	12
Pamilico River Estuary	905	3.93	0.92	2,840	12.3	2.89	7
Archipelago-Stockholm	720	3.48	--	5,990	28.5	--	19
Thames Estuary	12,300	109.8	15.40	51,800	462.5	64.8	10
Baptiste Lake	3.5	0.38	0.04	38	4.2	0.4	24
Tyne Estuary	1,142	190.3	20.70	4,500	750.0	81.8	9

TABLE 12. External Nutrient Loadings for the Chesapeake Bay and its Estuaries.

Ecosystem		Ecological Description	Surface Area (m^2) (10^6)	Volume (m^3) (10^6)	Average Depth (m)	Average Retention Time (yrs)
Patuxent	1963	Non-eutrophic	137	660	4.8	1.70
	1969-71	Eutrophic	137	660	4.8	1.70
	1978	Eutrophic	137	660	4.8	1.70
York	1969-71	Non-eutrophic	210	910	4.3	0.72
Rappahannock	1969-71	Non-eutrophic	400	1,780	4.5	1.27
James	1969-71	Eutrophic	600	2,400	3.6	0.39
Potomac	1913	Non-eutrophic	1,250	7,150	5.8	1.07
	1954	Eutrophic	1,250	7,150	5.8	1.07
	1969-71	Hyper-eutrophic	1,250	7,150	5.8	1.07
	1977-78	Eutrophic	1,250	7,150	5.8	1.07
Chesapeake Bay		Localized				
(Including Tribs)		eutrophic	11,500	74,000	6.5	1.16
(Excluding Tribs)		conditions	6,500	52,000	8.4	1.32
	1969-71					

TABLE 12. (cont'd)

		External Phosphorus			External Nitrogen			
		(g/yr)	($g/m^2/yr$)	($g/m^3/yr$)	(g/yr)	($g/m^2/yr$)	($g/m^3/yr$)	Atomic N/P Ratio of Loading
		(10^6)			(10^6)			
Patuxent	1963	170	1.24	0.26	930	6.7	1.4	12
	1969-71	250	1.82	0.38	1,110	8.1	1.7	10
	1978	420	3.06	0.64	1,500	11.4	2.4	8
York	1969-71	160	0.76	0.18	1,190	5.6	1.3	17
Rappahannock	1969-71	180	0.45	0.10	1,500	3.8	0.8	19
James	1969-71	1,780	2.70	0.70	10,300	15.6	4.2	13
Potomac	1913	910	0.73	0.13	18,600	14.8	2.6	46
	1954	2,000	1.63	0.28	22,600	18.1	3.1	26
	1969-71	5,380	4.30	0.80	25,200	20.2	3.5	11
	1977-78	2,520	2.01	0.35	32,800	26.2	4.6	30
Chesapeake Bay (Including Tribs)		15,000	1.30	0.20	109,100	9.5	1.5	16
(Excluding Tribs)	1969-71	7,350	1.10	0.10	70,160	10.8	1.3	22

Patuxent had the highest values. For the non-eutrophic York and Rappahannock systems, the phosphorus loadings were 0.76 and 0.45 $g/m^2/yr$, respectively. The loadings for the entire Chesapeake Bay, including estuaries, were 1.3 and 9.5 $g/m^2/yr$ for phosphorus and nitrogen, respectively, indicating that the system, while biologically productive, was not being stressed as much as the Potomac, Patuxent, and James.

In comparing the nitrogen to phosphorus ratios for the 1969-1971 period, the Patuxent, James, and Potomac appeared to have been nitrogen limited. The York, Rappahannock, and Chesapeake Bay appeared to have been phosphorus-limited systems.

The external data loadings for the Potomac in 1913 (26) and for the Patuxent in 1963 (14) in conjunction with the 1969-1971 loadings for the York and Rappahannock suggest that when the external phosphorus loading was 1.2 $g/m^2/yr$ or less, non-eutrophic conditions existed. Data for the Potomac vividly demonstrate that when phosphorus removal was instituted at the wastewater treatment facilities discharging into the upper estuary, the ecosystem reverted from a hyper-eutrophic condition in 1969-1971 to a eutrophic condition in 1977-1978. In 1977-1978, the nitrogen loading increased, mainly due to a larger contribution from the upper basin. The external total carbon loading in 1977-1978 was not significantly changed from the loading in 1969-1971 (1).

The nitrogen/phosphorus ratio of the external loadings in 1977-1978 was 30, indicating that phosphorus was limiting. Analysis of water quality data (1) of the upper Potomac estuary in 1977-1978 indicates N/P ratios of 30 to 40, also suggesting that phosphorus appeared to have been limiting. In addition, chlorophyll levels have been reduced by 20-30 percent since 1969-1971 and the transparency has increased by 20-30 percent. Total organic carbon has also been reduced by 30-40 percent, attributed primarily to a reduction in eutrophic conditions.

Discussion

Data from the two tables suggest that for estuarine ecosystems on the east coast of the United States, if the N/P ratio is above 16 and external phosphorus loadings are less than 1.0 $g/m^2/yr$, "excessive" eutrophic conditions will not prevail. These data further suggest that the "permissible" phosphorus loading is 0.75 $g/m^2/yr$ or less.

For estuarine ecosystems that are nitrogen limited (N/P ratio less than 16), the data in Tables 11 and 12 are somewhat conflicting with regard to suggesting a permissible loading for nitrogen. If a phosphorus loading of 0.75 is "permissible," it suggests, based on the N/P ratio, that the "permissible" nitrogen loading should be about 5.4 $g/m^2/yr$. The nitrogen loading for the Patuxent in 1963 was 6.7 $g/m^2/yr$, which is above the "permissible" state. The 1969-1971 nitrogen loading for the Pamlico River estuary was 12.8 $g/m^2/yr$, and was also nitrogen limited. However,

its eutrophic scale appears to have been similar to that of the Patuxent in 1963.

This difference may possibly be explained by 1) the existence of nitrogen fixation, 2) the occurrence of denitrification, 3) a possibly greater percentage of phosphorus loss to the sediment when compared to nitrogen, or 4) a difference in nutrient dynamics, including recycling. Further analysis of ambient water quality, including dissolved oxygen resources, may also explain this difference.

Except for the Potomac, the data in Table 12 reflect wastewater discharges with no phosphorus removal. If phosphorus removal (90 percent) were incorporated into all other wastewater treatment facilities that discharge directly into the Chesapeake Bay and its estuaries, phosphorus loading would be less than 1.0 $g/m^2/yr$ and the N/P ratio would be greater than 16. These loadings and ratios suggest that excessive eutrophic conditions would be averted. The response of the Potomac estuary to phosphorus control strongly supports this hypothesis.

Data for Albemarle Sound, the Potomac, York, and Rappahannock estuaries, and projections for the Chesapeake Bay are somewhat contrary to conclusions of Ryther and Dunstan (42). They suggest that for coastal waters, nitrogen is usually the critical limiting factor to algal growth and that phosphorus is usually in excess. They further suggest that removal of phosphorus in detergents and substituting nitrilotriacetic acid (NTA) would be counterproductive in controlling eutrophic conditions in coastal waters. Data developed in this report indicate that phosphorus control by advanced wastewater treatment appears to be a feasible method of alleviating excessive eutrophic conditions in some estuarine systems.

The comparison presented in this section has been on an annual basis. For estuarine systems with short hydrologic retention times and highly varying external loading, seasonal or monthly analyses may be required. In addition, an analysis of the N/P ratios, based on the reactive forms, may also be required.

SUMMARY

External Nutrient Budget Considerations

Data from detailed analysis of five ecosystems are summarized as follows:

1. The relative contribution of nutrients from air, land runoff, and wastewater sources can vary significantly from one ecosystem to another. For example, the relative contribution from wastewater discharges of phosphorus varied from 84 percent for the Potomac estuary to less than 5 percent for Lake Superior.

2. On a seasonal basis, the contribution of nutrients from land runoff exhibits the greatest variability of the three major nutrient sources. The contribution of nutrients is greatly influenced by the seasonal hydrologic cycle.
3. The contribution of nutrients from land runoff on an annual basis can vary over two-fold from year to year, again depending on the annual hydrologic cycle.
4. Since there appears to be a good correlation between stream flows and nutrient loadings from land runoff, statistical significance can be added to short-term nutrient budgets by the proper use of statistical techniques and the longer historical stream-flow records.
5. Historical external nutrient budgets can be developed from population data from municipal wastewater sources and from hydrologic data correlations for land runoff sources.

Impact and Scale of Eutrophication

A study of the impact and scale of eutrophication of Albemarle Sound, Pamlico River estuary, Potomac estuary, Hudson estuary, Oslo Fjord, and the New York Bight estuary suggests the following:

1. Oxidation of ammonia nitrogen can have a significant impact on the oxygen resources of an estuarine ecosystem. For the Potomac estuary, this oxidation process has about three times the impact on the oxygen resources than the oxidation of carbonaceous material from wastewater discharges.
2. The amount of organic carbon fixed due to the eutrophication process can be one of the major sources of organic carbon to estuarine ecosystems.
3. Data from the New York Bight, Oslo Fjord, and other estuarine ecosystems suggest that from 40 percent to over 75 percent of the organic carbon in these estuaries is attributed to the eutrophication process.
4. Anoxic conditions in the lower depths of many estuarine ecosystems can be attributed to the eutrophication process.
5. A scale of eutrophication for estuarine ecosystems of hyper-trophic, eutrophic, and non-eutrophic conditions is proposed.

Comparison of Nutrient Loading Versus Scale of Eutrophication

The study of 13 selected ecosystems and a detailed analysis of the Chesapeake Bay and its 5 major estuaries is summarized as follows:

1. Phosphorus loading varies from 0.04 for Lake Superior to over 190 $g/m^2/yr$ for the Tyne estuary. Nitrogen loading varies from 1.2 for the North Sea to over 750 $g/m^2/yr$ for the Tyne estuary.

2. Except for three estuarine ecosystems which receive large amounts of apparently toxic industrial wastewater, phosphorus and nitrogen loadings ($g/m^2/yr$) are generally indicative of the eutrophic condition of a given estuary.
3. Based on nitrogen/phosphorus ratio anlayses, six of the selected 13 estuarine ecosystems were phosphorus limited and seven were nitrogen limited.
4. From an analysis of the Chesapeake Bay and its five major estuaries, three estuaries appear to be nitrogen limited and two appear to be phosphorus limited. The two apparently phosphorus-limited estuaries were also considered to be non-eutrophic.
5. Data from 13 water bodies and the Chesapeake Bay and its 5 major estuaries suggest that if phosphorus loading is less than 1.0 $g/m^2/yr$, excessive eutrophic conditions can be prevented. A "permissible" phosphorus loading of 0.75 $g/m^2/yr$ is suggested.
6. The favorable response of the Potomac estuary to phosphorus control demonstrates that excessive eutrophic conditions may be alleviated in estuarine ecosystems depending on many factors, including nutrient loadings.
7. The studies suggest that use of the nutrient loading concept can yield insights as to the success of advanced wastewater treatment to prevent excessive eutrophic conditions in many estuaries. Utilization of advanced wastewater treatment to reduce phosphorus loads may be appropriate for estuaries where the major source of phosphorus is wastewater discharges.
8. For estuarine ecosystems with short hydrologic retention times and highly varying external loadings, seasonal or monthly analysis may be required.

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